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First Glacier Inventory and Recent Changes in Glacier Area in the Monte San Lorenzo Region (47°S), Southern Patagonian Andes, South America

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Abstract

We present the first glacier inventory of the Monte San Lorenzo region (47°35′S, 72°18′W) in the southern Patagonian Andes of Chile and Argentina. This region contains the largest and easternmost glaciers at these latitudes in South America. The inventory was developed using a combination of ASTER and Landsat ETM+ scenes from 2005 and 2008, respectively, and a semi-automatic band ratio approach to map glacier ice. Manual corrections were applied to include debris-covered ice and ice in cast shadows. We inventoried 213 glaciers that cover a 2005/2008 total area of ca. 207 km^2 and lie between 520 m and 3700 m in elevation. Landsat TM images acquired in 1985 and 2000 were subsequently used to assess changes in glacierized area over the 1985–2008 interval. Based on all available information, we determined an 18.6% reduction in the total glacier area since 1985. Glaciers smaller than 1 km^2 have shown highly variable (0–100%) relative areal reduction, whereas the formation and growth of proglacial lakes promoted rapid recession of the larger valley glaciers, which concentrate the major ice losses, representing ca. 32% of the total glacier area reduction. Glacier fragmentation has occurred for 50% of the ice bodies larger than 1 km^2. These results agree with the generalized pattern of glacier retreat observed throughout the Patagonian Andes, but the lack of detailed meteorological and glaciological data in the area preclude a more refined analysis of the climate-glacier relationships and processes explaining the recent glacier trends.

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Introduction

In contrast to the renewed interest and attention paid to the large outlet glaciers of the North and South Patagonian Icefields (e.g. Aniya et al., 1996; Rivera et al., 2007, 2012; Lopez et al., 2010; Willis et al., 2012; Aniya and Skvarca, 2012), other areas with smaller ice masses in the Patagonian Andes have received significantly less attention and are still poorly known and understood. This is arguably due to the remoteness of these glaciers and their lower relative significance for large-scale assessment such as those focusing on mountain glacier contributions to sea-level changes (e.g. Hock et al., 2009). However, the great number and variety of ice masses distributed across the southern Andes outside the Patagonian Icefields can provide useful, complementary information with numerous potential applications, for example for improving our understanding of the glacier-climate relationships in different environments and to help explain the recent glacier trends in the region.

Previous attempts to identify and inventory glaciers in Patagonia have generally relied on remote sensing data. Many earlier studies based their maps on aerial photographs (Bertone, 1960) but more recently the availability of satellite imagery has greatly improved the capacity of developing glacier inventories of large areas using a reliable, semi-automatic approach. These methods have been used for mapping the glaciers in the Northern and Southern Patagonian Icefields (e.g. Aniya et al., 1996; Rivera et al., 2007), in the Gran Campo Nevado further south at ca. 53°S (Schneider et al., 2007a), and in the islands south of the Magellan Strait (Isla Santa Inés, Monte Sarmiento, and Cordillera Darwin) (Bown et al., in press). Inventories of the smaller ice masses in the southern Patagonian Andes are scarce and generally focused on specific study sites, and currently there is no detailed information on the total glaciated area in Patagonia. In many cases, the extensive and persistent cloud cover together with the occurrence of summer snow storms in the southern Patagonian Andes can constitute a serious limitation for the collection of high-quality satellite imagery for glacier inventories in this region.

Numerous studies have documented the recent glacier fluctuations in this region over the past years/decades (e.g. Koch and Kilian, 2005; Aravena, 2007; Masiokas et al., 2009; Willis et al., 2012). These studies show a generalized retreat that is similar to that observed in other mountainous areas of the world, but there are still several areas where recent glacier behavior is poorly known. In this study we first identify and map all glaciers in the Monte San Lorenzo region (47°36′S, 72°19′W; Fig. 1), a little-known sector of the southern Patagonian Andes. Using satellite imagery from earlier years, we subsequently assess the recent areal changes of these glaciers over the 1985–2008 period.

Our study fits entirely within recent Federal initiatives of the governments of Argentina and Chile intended to inventory, monitor, and study all ice masses along the Andes. These initiatives are intended to provide reliable and comparable results from both sides of the Andes, which will be supported by well-documented techniques and background knowledge. The information regarding the frozen water reserves in the Andes can have numerous applications in policy, science, and education and will eventually be transferred to global data sets such as those maintained by the World Glacier

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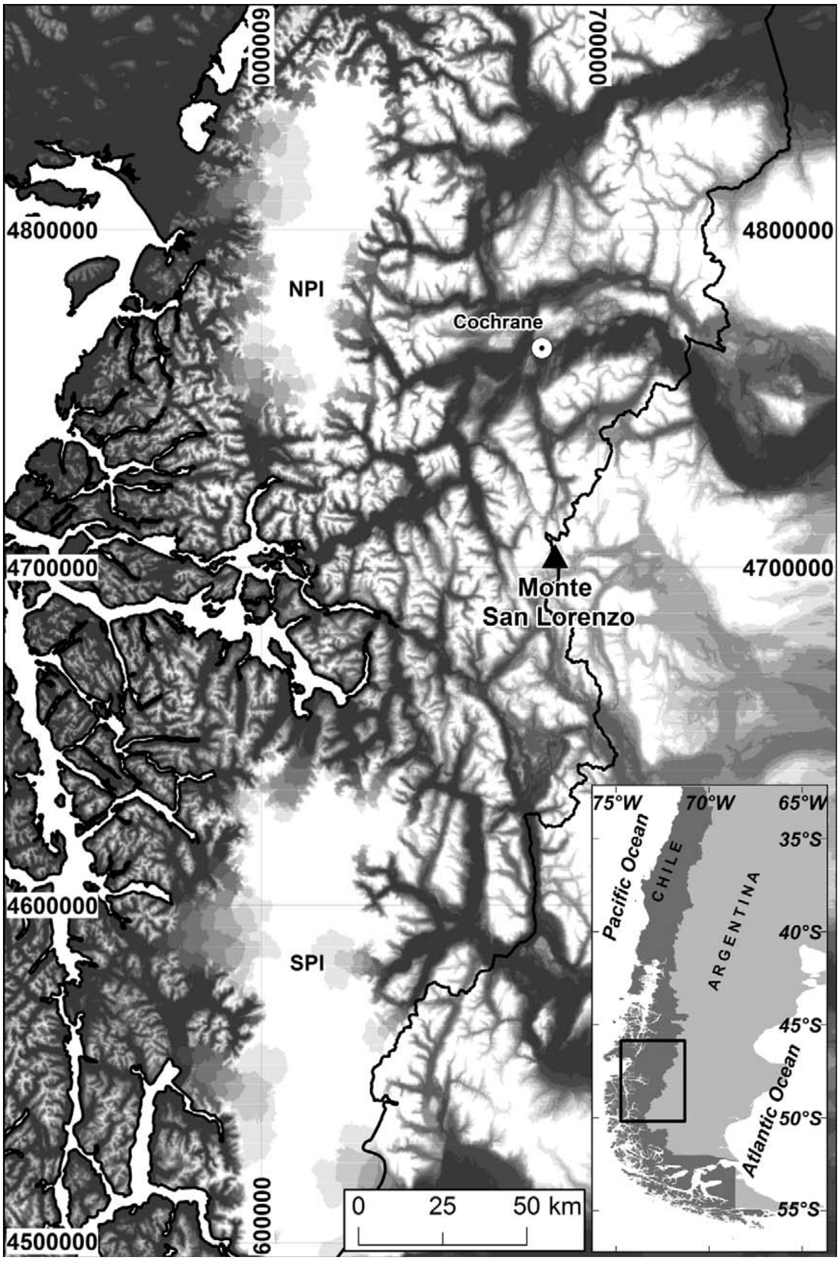

FIGURE 1. Location of the study area in the southern Patagonian Andes. NPI: Northern Patagonian Icefield. SPI: Southern Patagonian Icefield.

Monitoring Service (WGMS; http://www.geo.uzh.ch/microsite/wgms) and the Global Land Ice Measurements from Space initiative (GLIMS; Kargel et al., 2005). Together with other similar efforts in other glacierized areas across the Andes, our results have the potential of substantially improving the current knowledge about glaciers in less known areas of Patagonia and will hopefully stimulate further scientific research in this unique Andean environment. In this context, the principal objectives of this study are (1) to complete the first glacier inventory for the Monte San Lorenzo area, (2) to measure glacier area changes between 1985 and 2008, and (3) to discuss possible explanations for the recent changes.

Study Area

Monte San Lorenzo (3706 m; Fig. 1) is located at the international border between Chile and Argentina. Together with other minor peaks, this mountain range is relatively isolated from other glacierized areas, ca. 70 km east of the southern tip of the North Patagonian Icefield.

Since the time of the first complete reconnaissance trip in 1937 (De Agostini, 1945), when splendid photographs of Monte San Lorenzo and its main glaciers were collected, few studies of these glaciers are available; exceptions include recent frontal variations of some glaciers (Fernández et al., 2006; Aravena, 2007), the glacial geology and geomorphology of the Holocene (Wenzens, 2002, 2005) and the Little Ice Age (LIA) periods (Aravena, 2007; García-Zamora at al., unpublished data). Despite these studies, a complete and comprehensive glacier inventory and an assessment of changes in glacier extent for this area have not been carried out.

For the purposes of this study, we divided the region into four main sectors distinguished by local topographic characteristics and glacier morphology. The four sectors are Cerro W, Cerro Peni-

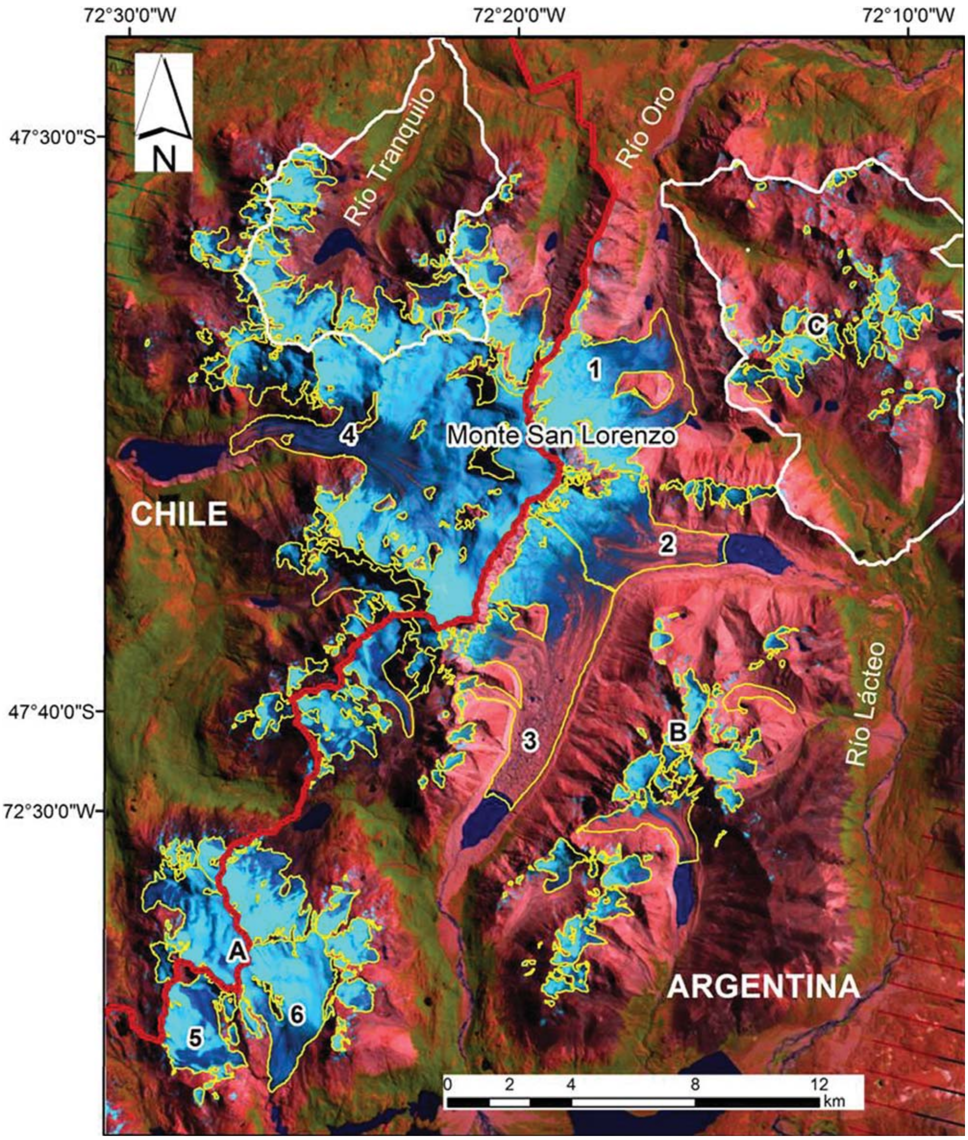

FIGURE 2. False color composite Landsat ETM+ from 4 February 2008, showing Monte San Lorenzo and surrounding areas with inventoried glaciers in yellow. Sub-basins inventoried using this 2008 image are shown in white, the remaining sectors were inventoried using a late summer 2005 ASTER scene. International border in red line. (A) Cerro W; (B) Cerro Penitentes; (C) Cerro Hermoso; (1) Río Oro Glacier; (2) Río Lácteo Glacier; (3) San Lorenzo Glacier; (4) Calluqueo Glacier; (5) West Sobral Glacier ; (6) Sobral Glacier.

tentes, Cerro Hermoso, and Monte San Lorenzo (Fig. 2). The Monte San Lorenzo and Cerro W massifs are shared between Chile and Argentina, whereas the Cerro Penitentes and Cerro Hermoso are entirely located on Argentinean territory. Most ice bodies in the study area are mountain and cirque glaciers, but the four largest glaciers are valley glaciers that reach the lower elevations in the area (see glaciers Calluqueo, Río Oro, Río Lácteo, and San Lorenzo Sur in Fig. 2). They have accumulation areas interconnected in compound basins and terminal parts covered by debris. LIA moraines confine the glacier tongues and often dam proglacial lakes, which began forming sometime prior to 1969, according to aerial photographs, and have enlarged since then. At present the largest proglacial lake is ca. 3.5 km long at the front of Calluqueo Glacier (Fig. 2).

Due to the interaction between the dominant westerly winds and the N–S orientation of the Patagonian Andes, environmental conditions in the San Lorenzo area (as in other areas along the southern Patagonian Andes) exhibit a strong precipitation gradient. It has been estimated that ca. 10 m of annual precipitation fall on the Southern Patagonian Icefield, decreasing to less than 300 mm within 100 km east of the main divide (Villalba et al., 2003). Temperature regimes are less extreme and vary from maritime on the western side of the main Andes to continental on the eastern side. The Monte San Lorenzo area has a transitional maritime to continental climate with a wide thermal amplitude and a narrow range of mean monthly precipitation. The nearest meteorological station is at Cochrane, (47°14′S, 72°33′W; 182 m a.s.l., 45 km northwest of Monte San Lorenzo) where the mean annual precipitation and temperature are 731 mm and 8.1 °C, respectively (Aravena, 2007).

Data Sets and Methods

We based most of the analyses on a set of ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), Landsat TM, and Landsat ETM+ orthorectified satellite images dating from 1985, 2000, 2005, and 2008 (Table 1). These images were selected due to their low seasonal snow and cloud coverage and were obtained from the U.S. Geological Survey (USGS) Earth Resources Observation and Science Center (EROS). The projection used was UTM zone 19 south, WGS84 datum. The ASTER scene

TABLE 1

Summary of Landsat and Aster scenes used for this study.

Platform/Sensor	Scene ID	Pixel Resolution	Date of acquisition (yyyy-mm-dd)
Landsat TM	LT52310931985027AAA10	30	1985-01-27
Landsat ETM+	LE72310932000061AGS00	30	2000-01-03
Aster	AST14DMO 00302202005143546	15	2005-02-20
Landsat ETM+	LE72310932008035EDC00	30	2008-02-04

from summer 2005, which presents ideal (minimum) seasonal snow conditions for glacier mapping, presents, however, cloud-covered areas (Cerro Hermoso massif and Río Tranquilo basin; Fig. 2). For these particular sectors covered with clouds in the ASTER scene, the glacier inventory was based on a Landsat ETM+ scene from late summer of 2008. The Scan line Corrector (SLC) of the Landsat 7 satellite failed in 2003, and hence it is relatively unusual to be able to use Landsat ETM+ data for glacier mapping. However, in this particular case we were able to use the 2008 image because glaciers are located in the center of the scene. In order to assess areal changes of glaciers for the 1985–2008 period, images were co-registered using an image to image process, with the ASTER 2005 image as basis and 15 manually selected Ground Control Points (GCP) that were obtained for each scene, yielding an RMS error lower than 0.7 pixels (ca. 20 m error for the Landsat scenes).

The Shuttle Radar Topography Mission (SRTM v.4) 90 m resolution Digital Elevation Model (DEM) was used for automatic delineation of hydrological basins. In some cases the sub-basins were manually corrected due to artifacts in the DEM. The model was also used to calculate glacier morphometric parameters such as minimum and maximum elevation, slope, and aspect, and to obtain glacier hypsometry. As the SRTM DEM was acquired during February 2000, these morphometric data should correspond approximately to the situation of glaciers observed in the Landsat ETM+ March 2000 scene.

Bare ice identification and mapping in the study area were achieved in a semi-automatic approach by first calculating band ratios of the raw Digital Numbers of Landsat TM3/TM5 and ASTER NIR3/SWIR4 scenes using ENVI 4.7 software. The thresholds for properly identifying bare ice and snow vs. other surfaces in the resulting images were determined interactively (final thresholds: 2.6 for Landsat and 1.0 for ASTER). These multispectral automated glacier mapping techniques have been exhaustively tested in the last decade (Paul et al., 2002; Paul and Kääb, 2005; Raup et al., 2007) and proven to yield strong, reliable results. This method, however, frequently and mistakenly includes proglacial lakes, omits ice and snow in cast shadows, and misses debris-covered ice. Therefore, glacier outlines were inspected carefully and were manually corrected using ArcGis 9.3 software when the above problems were detected. Following the Global Land Ice Measurement from Space (GLIMS) project guidelines, the minimal extension for a group of pixels to be considered a glacier or perennial snowfield was established at 0.01 km^2. Removal of smaller snow banks, internal rocks and other small areas detected within cast shadows areas were partly corrected by means of a median filter with a 5 $\times$ 5 kernel (Racoviteanu et al., 2009). Scenes from 1985 and 2005 consistently lack seasonal snow, thus glacier outlines should be reliable. The Landsat 2008 scene has little seasonal snow, but in a few cases, when this hindered accurate glacier mapping (particularly on small snowfields), outlines were manually corrected based on the visual inspection of composite Landsat (bands 5-4-3) and ASTER (3-2-1) contrast-enhanced scenes.

In order to validate the results from the automated analysis, Landsat and ASTER band ratios were tested against manual digitations of glaciers spread over the study area, done by four experienced analysts. Landsat TM3/TM5 ratios provided slightly better results than TM4/TM5 (+1.37% and −3.27%, respectively) with the former being more efficient in identifying internal rocks and shadow areas, whereas ASTER NIR3/SWIR4 performed better than NIR2/SWIR4 (−0.45% and +1.45%, respectively).

Results

GLACIER INVENTORY

For the entire area we inventoried a total of 213 ice bodies larger than 0.01 km^2 with a total glacierized area of ca. 206.87 km^2 (Table 2, Fig. 3). This inventory is based on the ASTER 2005 scene, except for the Cerro Hermoso massif and the Rio Tranquilo where the inventory is based on the Landsat 2008 scene (Fig. 2).

Smaller glaciers (0.01–0.1 km^2 and 0.1–0.5 km^2 area classes), which consist of snowfields, glacierets, and ice aprons, are much more numerous than the larger mountain and valley glaciers of the larger classes (5–10 km^2 and >10 km^2) but represent a much smaller total ice area (Fig. 3). In fact, more than 51% of the total ice bodies are smaller than 0.1 km^2, but they represent <2% of the total ice-covered area. In comparison, glaciers larger than 5 km^2 contribute no more than 0.4% of the total inventory by number but represent more than 61% of the total glacier area.

A total of 102 ice bodies were mapped in the Monte San Lorenzo itself, which account for an ice-covered area of ca. 139.34 km^2, the largest ice body being Calluqueo Glacier with an area of 45.3 km^2 (Fig. 2). The Cerro Penitentes massif is characterized by cirque glaciers, commonly 1–5 km^2 in average size, and several debris covered tongues. A total of 37 glaciers in this massif covered an area of 14.9 km^2 in 2005. The Cerro Hermoso massif is the least glacierized sector, with an area of 7.8 km^2 distributed among 41 ice bodies, most of them characterized as glacierets (Fig. 2). There are, however, a few mountain and cirque glaciers, mainly south-facing bodies with areas larger than 2 km^2 and exhibiting debris-covered snouts. Outside the Monte San Lorenzo, the largest glaciers are located on the Cerro W massif. This peak is situated directly to the south of Monte San Lorenzo, and has a total of 23 ice bodies covering 36.7 km^2, mostly composed of clean ice (Fig. 2).

TABLE 2

Number of glaciers and their corresponding surface area mapped in Monte San Lorenzo and surrounding peaks for 2005–2008. Total Region excludes Cerro Hermoso massif and Río Tranquilo sub-basin.

Sub-basin	Number of glaciers per class (km^2)						
	0.01–0.1	0.1–0.5	0.5–1	1–5	5–10	>10	TOTAL
Total Region 2005	78	43	12	15	4	4	156
Cerro Hermoso 2008	24	12	5	0	0	0	41
Río Tranquilo 2008	7	2	2	5	0	0	16
TOTAL	109	57	19	20	4	4	213
%	51.17	26.66	8.92	9.38	1.87	1.87	100

Glacier areas	Glacier area class (km^2)						
	0.01–0.1	0.1–0.5	0.5–1	1–5	5–10	>10	TOTAL
Total Region (km^2) 2005	2.6	10.6	10.4	34.2	28	98.2	184.1
Cerro Hermoso 2008	0.7	3.1	4.0	0	0	0	7.8
Río Tranquilo 2008	0.3	0.9	1.6	12.2	0	0	15
TOTAL km^2	3.6	14.6	16.0	46.4	28	98.2	206.9
Area %	1.8	7	7.7	22.4	13.6	47.5	100

GLACIER HYPSOMETRY, SLOPE, AND ASPECT DISTRIBUTION

Figure 4, part A, depicts the hypsometric distribution (Jiskoot et al., 2009) for the total glacierized area, differentiating clean from debris-covered ice. The basic elevation data were derived from the SRTM DEM and are used here to estimate the approximate hypsometry, slope, and aspect of the glaciers mapped in the 2005/2008 scenes. Glaciers are distributed over a wide altitudinal range starting at ca. 520 m (front of Calluqueo Glacier) up to 3700 m at the summit of Monte San Lorenzo. Whenever possible, we also identified the transient snowline for the larger glaciers (results not shown) in the late-summer (20 February 2005) ASTER image. The resulting snowlines were mapped by manual digitization and were then overlapped to the SRTM DEM in order to obtain the mean altitude. We detected a local asymmetry attributed to the marked precipitation gradients in the region: in the western sectors the transient snowline was mapped at around 1700–1750 m, whereas on the eastern, drier sectors this feature was mapped slightly higher, at around 1800 m (standard deviations can reach up to ca. 42 m for individual snowlines). These values agree with similar determinations reported by Wenzens (2002) for this area. Using SRTM data, the glacier hypsometry (Furbish and Andrews, 1984; Rivera et al., 2011) was derived for the main glaciers. Taking the transient snowlines as a surrogate for the true ELA, we determined the Accumulation Area Ratios (AAR) of the largest glaciers, which yielded contrasting patterns. Río Oro, Río Lácteo, and San Lorenzo valley glaciers (Fig. 2) have single basin accumulation areas with small AARs (between 0.1 and 0.5), whilst the elevation ranges between 900 m and 3700 m. In contrast, an AAR of 0.77 was determined at the Calluqueo Glacier, which ranges in elevation from 520 m to 3700 m and has a large, complex accumulation area with several cirques. This AAR value is unexpectedly high for a fast-retreating glacier and probably reflects the recent drastic reduction of the lower portion of the ablation area (Fig. 5). The formation and rapid growth of a large proglacial lake may have also played an important role in the glacier's enhanced retreat.

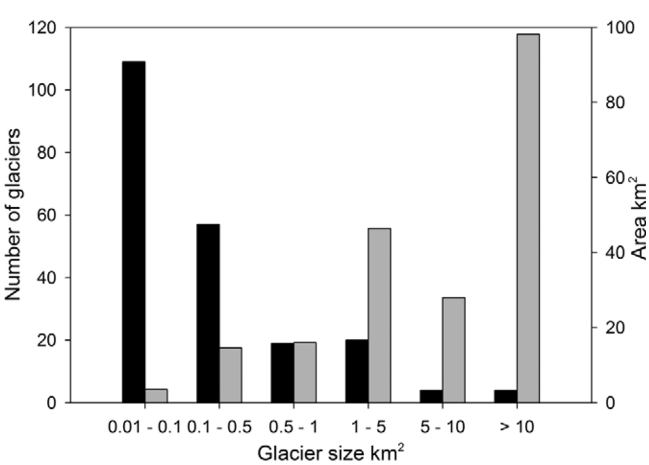

FIGURE 3. Glacier inventory showing the relationship between number of glaciers (black bars) and the area covered by different glacier size classes (gray bars).

Cerro W has mountain glaciers that do not reach such high altitudes and have a more even altitudinal distribution. The hypsometry of two glaciers in this area (not shown here) reveal that they have most of their area concentrated at relatively high elevations (around 1900 m), whereas for the Río Oro, Río Lácteo, and San Lorenzo glaciers the hypsometric curves peak around 1500 m, i.e. below the regional ELA reportedly situated around 1800 m (Wenzens, 2002).

Figure 4, part B, shows the scatter of glacier mean slope with respect to glacier size, where the general trend is for larger glaciers to have lower slopes. This is reasonable as the smaller ice bodies are hanging ice aprons or occupy steep couloirs, whereas the large glaciers have level accumulation areas and large glaciers fill the valley floors with flatter tongues. Results also show that most glaciers have a southeastern orientation (Fig. 6), which is consistent with other glacierized regions in the southern hemisphere. Glaciers with northern aspects show less altitudinal scatter than neighboring glaciers with southern aspects, suggesting that mean elevation re-

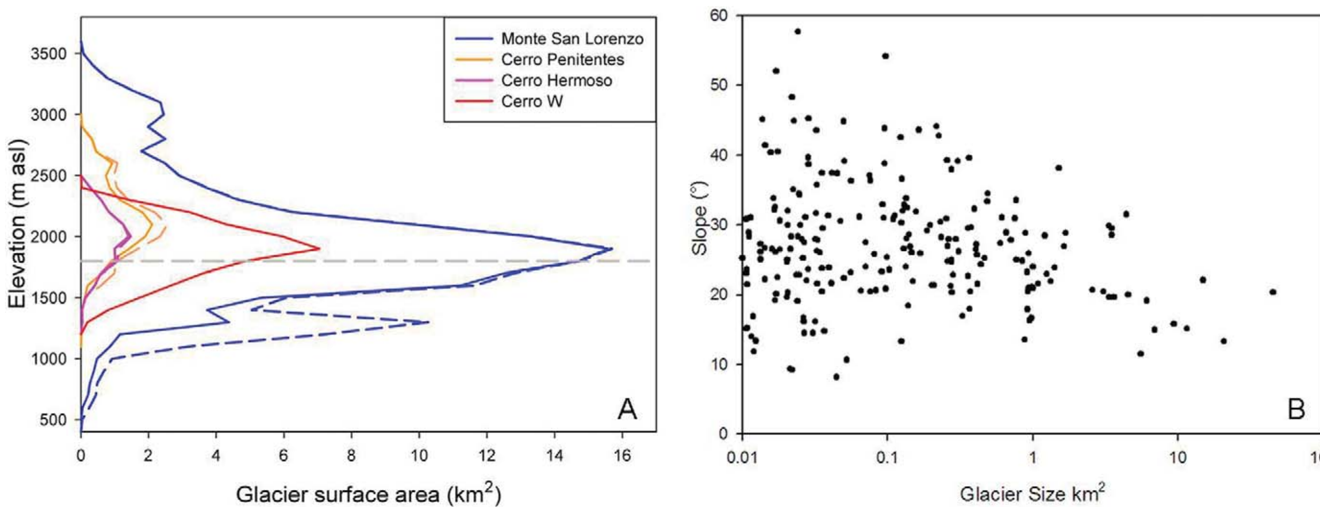

FIGURE 4. (A) Hypsometric distribution for the glaciated area in the Monte San Lorenzo region. The bare ice is represented by solid lines and the debris-covered portions in long dashed line. The horizontal dashed gray line indicates the ELA at 1800 m as reported by Wenzens (2002). (B) Variation of mean slope vs. glacier size; small ice bodies exhibit a broader scatter than larger glaciers.

sponds more to exposure to solar radiation than to particular topographic factors. However, besides the variations depending on the orientation, we found that the differences in mean elevation were generally more noticeable between the western and eastern glaciers (eastern units located usually higher) due to orographic effects.

GLACIER AREAL CHANGES

Glacier counts for 1985 and 2008 show that the number of glaciers has decreased, with some small glaciers having disappeared over the study period (Fig. 7). However, as some of them disappear, new ones appear at the expense of large glaciers through fragmentation and thus the number of glaciers is not a significant indicator of ice area reduction. In general, the eastern and southeastern slopes have experienced, in absolute terms, the largest glacier losses compared to slopes oriented in other directions in this area (Fig. 6). In addition, analysis of surface area changes shows that the glacier shrinkage is not constricted to the lower, ablation areas, but is also taking place in the accumulation areas due to dry calving on steep slopes, with hanging glaciers and ice aprons rapidly degenerating. This pattern is also observed in the accumulation areas of larger glaciers, which show progressively larger internal rock outcrops over the study period (Fig. 5). Figure 6 shows the aspect of the lost ice areas. A dominant trend is that east to southeast slopes have experienced the largest losses, whereas west to northwest slopes represent a much smaller loss in absolute terms (km^2) but maximum in percentage terms.

The wide scatter in percentage reduction is notable on small-sized glaciers and is less variable and markedly lower for larger ice bodies (Fig. 7). Our analysis indicates that almost 40 glaciers have completely disappeared since 1985, the majority of which had areas smaller than 0.1 km^2 (the largest glacier to have vanished was 0.259 km^2; Fig. 7). The broad range in relative reduction observed in these small units may be related to the fact that these ice masses can be found in different settings, often in exposed slopes but also in cirques, couloirs, and shadow zones which favor their preservation and make them less susceptible to climatic variability.

The retreat rates of the glaciers in the study area have been roughly similar in relative terms (i.e. considering total frontal retreat vs. total glacier length). However, the loss of ice is clearly more conspicuous in the case of the larger valley glaciers than in the smaller units. We recorded a total ice loss of 44.3 km^2 between 1985 and 2008. Of this total glacier loss, the shrinkage of the larger valley glaciers accounts for ca. 14.4 km^2 (or 32%). In most cases the frontal recession of these valley glaciers has been promoted by rapidly growing proglacial lakes (Fig. 2). Frontal recession of the San Lorenzo, Río Lácteo, Río Oro, and Calluqueo glaciers was estimated at ca. 1300 m, 2070 m, 430 m, and 580 m, respectively, over the last three decades. These values correspond to average retreating rates of 56 m a^{-1}, 90 m a^{-1}, 19 m a^{-1}, and 25 m a^{-1} for these glaciers. Field surveys and analyses of remote sensing data indicate that, in addition to the areal reduction observed at these sites, in most cases these glaciers have also experienced significant ice mass losses due to surface thinning of the lower, debris-covered tongues.

Discussion and Conclusions

This study presents new, well documented information about the current state and recent behavior of glaciers in the Monte San Lorenzo region, a little-known glacierized sector located to the east of the large North and South Patagonian Icefields in South America. The glacier inventory of this area yielded a total of 213 ice bodies covering an area of ca. 207 km^2. Although most of these units are relatively small, there are also a few large valley glaciers (up to 45 km^2 in size) that concentrate, in absolute terms, the majority of the glacierized area (Table 3). The results show that the use of medium resolution satellite imagery and a semi-automatic band ratio approach (Paul and Kääb, 2005; Raup et al., 2007; Paul and Andreassen, 2009; Racoviteanu et al., 2009) constitute a reliable way of detecting clean glacier ice in these remote mountainous environments. However, manual corrections of the glacier boundaries by experienced operators remain crucial where glaciers such

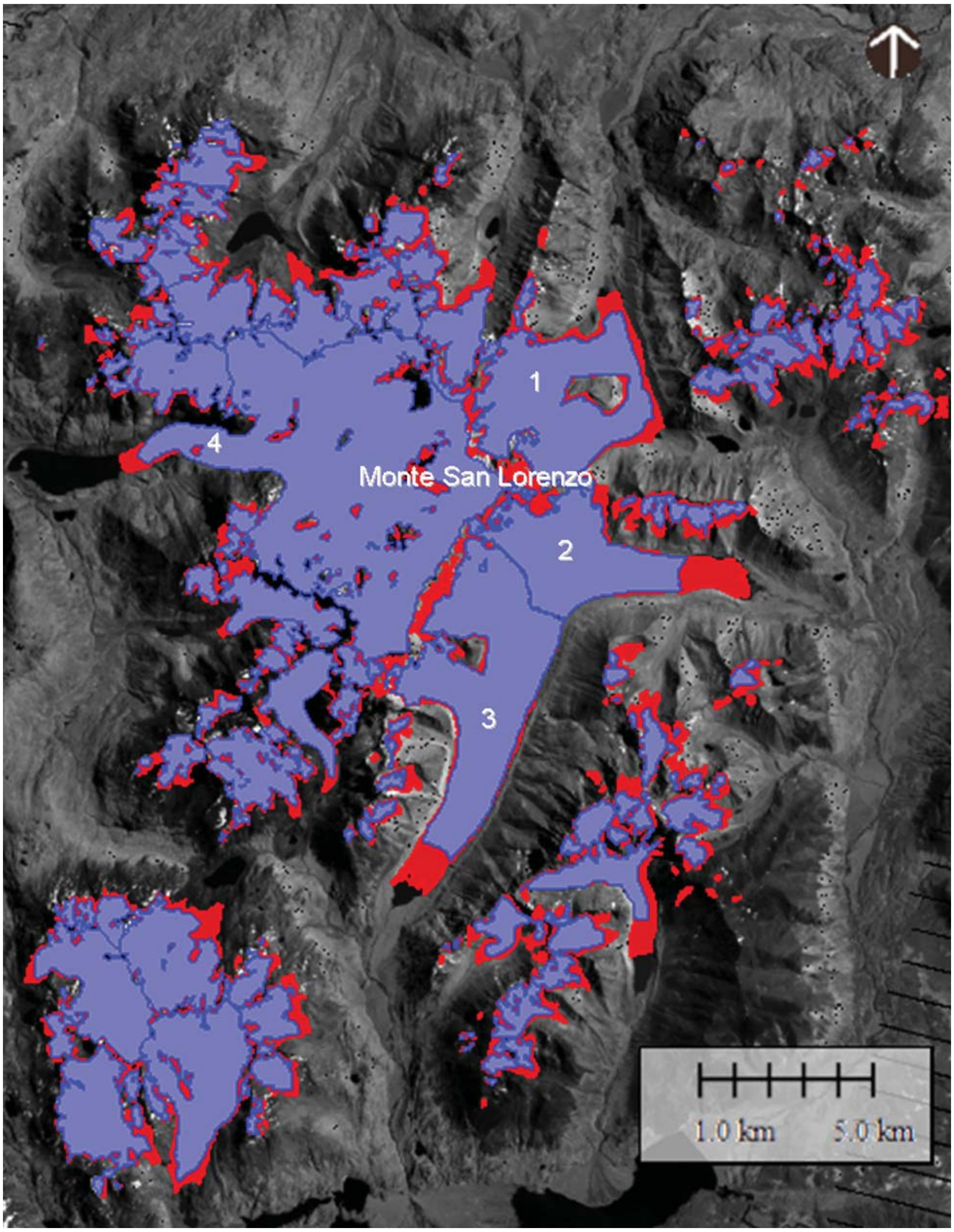

FIGURE 5. Glacier areal changes between 1985 in red and 2008 in blue. 1: Río Oro Glacier; 2: Río Lácteo Glacier; 3: San Lorenzo Glacier; 4: Calluqueo Glacier.

as those studied here have considerable portions in cast shadows or covered by debris.

Various types of error can be introduced when mapping glacier outlines from satellite images, and they differ in origin, magnitude, and ease of quantification (Paul and Andreassen, 2009). Technical error, which is related to orthorectification (or misregistration between images) is relatively small and can be statistically assessed by means of the root-mean-squared-error (RMSE). Interpretation or methodological error is linked to the mapping of ice divides (which may change in time, but were assumed as static in this study), debris-covered ice, seasonal snow conditions, and areas in cast shadows. This type of error can be comparatively large, highly variable, and difficult to assess. In this case the experience of the operator is crucial and a comparison of glacier outlines produced by different operators may help assess the magnitude of these errors. Paul et al. (in press) showed that the digitizing accuracy when mapping glacier limits on satellite images is comparable to the pixel size. Assuming an error of one pixel over the entire perimeter of the glaciers, we found a maximum error of ca. 35% for small glaciers (<1 km^2) and 7% for larger glaciers in the case of Landsat scenes, whereas for ASTER images the errors were ca. 17% and 3%, respectively. Another source of error is associated with the particular glacier mapping algorithm used in each case. As mentioned above, here we used a technique that has been tested in several other glaciated regions in the world and shows consistent, reliable results for the identification of bare ice and snow. In order to validate the results from the automated analysis derived from Landsat and ASTER band ratios, the final outlines were compared against those obtained from complete manual digitization of glaciers. Considering the manual mapping as the reference measurement with higher accuracy, Landsat TM3/TM5 ratios provided slightly better results than TM4/TM5 (+1.37% and −3.27%, re-

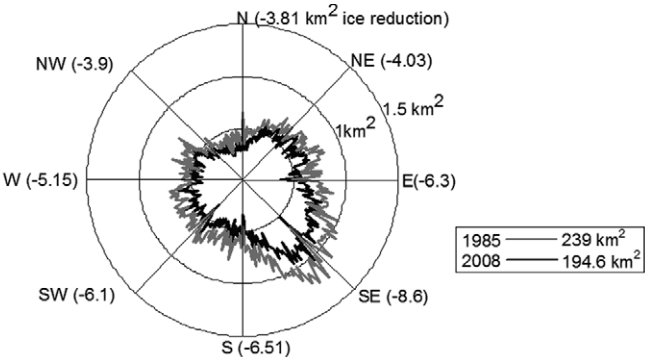

FIGURE 6. Orientation of the glaciated area in the San Lorenzo region in 1985 (gray) and 2008 (black). Values in parentheses indicate absolute ice losses in square kilometers for each cardinal sector. Note that although most glaciers are located on slopes oriented towards the southeast, the percentage reduction in glaciated area is roughly similar for all cardinal sectors (ranging between 14% and 23%).

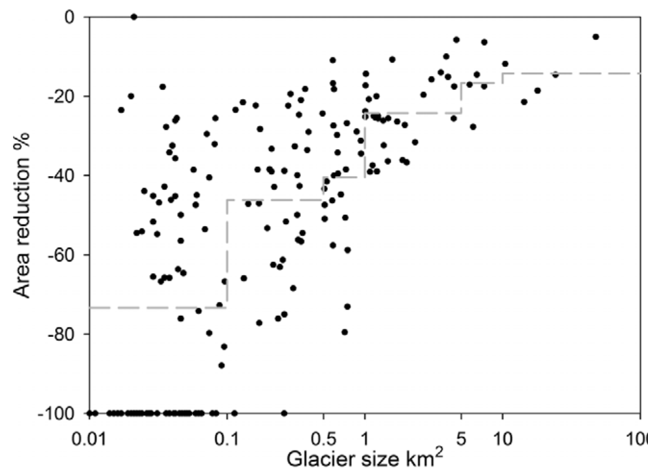

FIGURE 7. Relative changes in area between 1985 and 2008 for glaciers of different size in the Monte San Lorenzo area. The gray line represents the average areal change per size class. Over the past three decades the largest glaciers have experienced the lowest relative reductions in surface area.

spectively), with the former being more efficient in identifying internal rocks and shadow areas. The comparison with ASTER showed that the ratio NIR3/SWIR4 performed better in general than NIR2/SWIR4. Overall, we found that the errors in glacier mapping were relatively small, supporting the use of a semi-automatic approach to identify clean ice portions of glaciers in this region.

The total glacier area in the Monte San Lorenzo region has decreased by 18.6% over the 1985–2008 period (average reduction of −0.8% of the 1985 area per year). The images available indicate that the retreat rates of the glaciers in the area have increased in recent years; 2000–2008 is the period which shows the highest retreat rates with an overall 2.6% of ice loss per year (Table 4). East-facing glaciers have experienced, in general, the highest retreat rates compared to other glacier orientations in the area (Fig. 6). Associated with the overall process of glacier shrinkage, we also found evidence of fragmentation of the largest glaciers and in general in 50% of the ice bodies (which results in an increase in the number of units of smaller size), and the complete or almost complete disappearance of several small units. Although glacier fragmentation leading to increased retreat has been addressed by Paul et al. (2004) in the Alps and Jiskoot et al. (2009) in the Canadian Rockies, our analysis does not conclusively support that glacier fragmentation has necessarily led to higher retreat rates. Discarding the glaciers that have completely disappeared since 1985, glaciers which have experienced fragmentation averaged a reduction of 43%, whilst those that did not suffer the fragmentation process showed a 37% reduction.

Despite these specific differences, this recent pattern of glacier mass loss at San Lorenzo is consistent with the situation observed elsewhere in Patagonia (Masiokas et al., 2009; Lopez et al., 2010; Davies and Glasser, 2012). This suggests that a regional or larger scale forcing connected to atmospheric changes, rather than localized factors, can at least partly explain the observed glacier behavior in this region.

The few existing climate stations in the southern Patagonian Andes have relatively complete climate records since 1985, but in almost all cases they are located farther away and at lower elevations than the glaciers investigated here and elsewhere. The studies of 20th century regional surface climate trends in southern Patagonia (e.g. Rosenblüth et al., 1995; Villalba et al., 2003) have reported warming trends south of 46°S. Villalba et al. (2003) also produced tree-ring-based temperature reconstructions and determined that the warming observed in recent decades at the southern-

TABLE 3

Glacier size classes with their respective count and surface for 1985 and 2008, glacier shrinkage, mean size, and relative contribution to the total amount of glaciated surface.

Class km^2	1985		2008	Difference		Mean size	Area
	(n)	(km^2)	(km^2)	(km^2)	(%)	(km^2)	(%)
0.01–0.1	86	3.4	1	–4.3	–70.6	0.02	0.5
0.1–0.5	39	9.9	5.6	–5.6	–43.4	0.16	2.9
0.5–1	25	15	9.4	–2.4	–37.3	0.45	4.8
1–5	31	63.4	50	–13.4	–21.1	1.6	25.7
5–10	6	33	28	–5	–15.2	4.67	14.4
>10	5	114.2	100.6	–13.6	–11.9	20.12	51.7
TOTAL	192	238.9	194.6	–44.3	–18.6	1.37	100

TABLE 4

Ice covered surface, absolute and relative glacier change, and annual change.

Area (km^2)			Glacier change 1985–2008		Glacier change per year (km^2)		
1985	2000	2008	(km^2)	(%)	1985–2000	2000–2008	Total 1985–2008
239	215.4	194.6	–44.4	–18.6	–1.6	–2.6	–1.9

most stations was unusual in the context of the last 400 years. In contrast, Carrasco et al. (2002) estimated a temperature increase in the Southern Patagonian Icefield until the mid 1980s, but no significant trend in the last two decades. Falvey and Garreaud, (2009) found no significant trends in surface temperature and upper layer temperature between 37°30′S and 47°30′S for the 1976–2006 period.

Larger-scale assessments of precipitation trends in southern Patagonia have found contrasting patterns in different areas and have also stressed the lack of surface climate data in the region. In a comprehensive assessment of available surface records, Carrasco et al. (2002, p. 40) concluded that there is a ‘‘high spatial variability of precipitation over the region and no clear conclusion can be interpreted from the available data with respect to significant changes during the last century.’’ Aravena and Luckman (2009) reported an increase in precipitation around 1960 for the region east of the Andes between 45°S and 47°S followed by a decreasing trend. In a more recent assessment, Garreaud et al. (in press) indicate that reanalysis data (NNR and ERA40) exhibit a reduction of the westerly flow over the Patagonian Andes in north-central Patagonia for the period between 1968 and 2001. This reduction in westerly flow is congruent with an approximate precipitation decrease of 300 mm per decade at the main western peaks around the latitudes of Monte San Lorenzo. However, given the dramatic precipitation gradients in the area and that our study area is approximately 170 km from the Pacific coast towards the easternmost reaches of the Patagonian Andes, it is difficult to determine precisely the relative changes in climate that have occurred at the San Lorenzo glaciers over recent decades. Our analysis of 1969–2008 records (not shown) from the Lord Cochrane meteorological station, located 46 km to the northwest of Monte San Lorenzo, showed no conclusive trends in winter precipitation nor summer temperature. However, this station is at 180 m a.s.l. and thus is not entirely representative of the conditions and climate changes that may have occurred at higher elevations around the Monte San Lorenzo glaciers.

The uncertainties, lack of data and limitations discussed above highlight the urgent need for detailed, *in situ* meteorological and glaciological data to properly assess the relative and specific influence of recent climate changes on the observed glacier behavior at the San Lorenzo region (and other glacierized areas across the Patagonian Andes). Glaciers located towards the western, wetter sectors of the study area are probably in a transition zone between maritime and continental climate conditions, whereas glaciers facing the eastern Patagonian steppe are under a more continental regime. However, assessments of the relative sensitivity of particular glaciers to local changes in temperature and precipitation require detailed data collected on these glaciers and monitoring programs that ensure the proper and uninterrupted collection of data over the years. Besides these requirements for actual, near-time meteorological and glaciological records, other possible future research avenues to improve the understanding of the glacier-climate relationships may include the incorporation of earlier information about glacier frontal positions from aerial photographs, historical documents, and dendro-geomorphological determinations of LIA moraines at selected sites.

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